The 2010 Chilean Tsunami on the California Coastline

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ABSTRACT: At 2:55 AM PDT, a little over four hours after the Chilean earthquake origin time, the West Coast Alaska Tsunami Warning Center placed the entire California coast in a Tsunami Advisory. The Advisory forecast tsunami amplitudes ranging from approximately 0.3 to 1.4 meters and strong currents in bays and harbors. Hourly conference calls were held with the county operational areas and most counties cleared beaches and limited access to harbor areas. The highest amplitudes were predicted for San Luis Obispo County and areas south. The tsunami initially arrived at San Diego at 12:02pm on February 27, and moved progressively up the coast over the next hour and a half. Peak amplitudes at tide gauge locations in the state ranges from 0.12 meters to a high of 0.91 meters at Santa Barbara. At most locations, the strongest surges were recorded within the first two hours but for some locations, like Crescent City and Santa Barbara, the largest surge occurred 5-6 hours after the initial onset. At many locations, the tsunami activity lasted for more than a day, and in some areas exacerbated ambient flooding from severe storm activity. Harbors in southern and central California were impacted the most by estimated tsunami currents ranging from five to 15 knots, with minor to moderate damage occurring in several areas. Damage estimates for the state could climb to several million dollars. Estimated (from videos, eye-witness accounts) and recorded (instrumented) tsunami current velocities could provide an important validation and/or calibration tool for numerical tsunami modeling methods and databases of existing model runs.

Background: On February 26th, 2010, at 10:34 PM PDT, a magnitude 8.8 earthquake struck the Maule region of central Chile. The earthquake was generated along the plate boundary where the Nazca Plate is being subducted under the South American Plate, approximately 300 km north of the magnitude (M_w) 9.5 1960 earthquake (Figure 1). Preliminary reports indicate that damage from the earthquake was significant to older buildings and buildings with limited reinforcement. A large tsunami was generated locally, causing severe damage to coastal towns and port facilities.

Approximately 9,000 km (5,600 mi) to the north, California's 1,100-mile coastline has 20 counties and over 80 cities that are vulnerable to tsunamis. The California Emergency Management Agency (CalEMA) and its partner science organization, the California Geological Survey (CGS), work closely with the National Oceanic and Atmospheric Administration (NOAA) West Coast and Alaska Tsunami Warning Center (WCATWC) and regional emergency managers during a tsunami alert. The following documents the activities of the WCATWC, CalEMA, CGS, and other geoscientists that collected data and provided information to help local emergency managers determine the best course of action to protect the public and property against the teletsunami from Chile (Figure 2).

NOAA's West Coast and Alaska Tsunami Warning Center (WCATWC) Tsunami Alert Criteria

California is located within the WCATWC Area-of-Responsibility, and has four regional National Weather Service offices with Warning Coordinating Meteorologists (WCMs) to assist with "tsunami alerts." To help clarify the tsunami alert messaging, new criteria were recently developed for alerting this region about a potential tsunami or tsunami hazards (summarized from Whitmore and others, 2008):

Tsunami Information Statement - issued to inform and update emergency managers and the public that an earthquake has occurred, or that a tsunami warning, watch or advisory has been issued elsewhere in the ocean.

Tsunami Watch - issued to alert emergency managers and the public of an event which may later impact the watch area; may be upgraded to a warning or advisory - or canceled - based on updated information/analysis.

Tsunami Advisory - issued due to the threat of a potential tsunami which may produce strong currents or waves dangerous to those in or near the water (typically tsunami forecast amplitudes 30 cm to 1 m).

Tsunami Warning - issued when a potential tsunami with significant widespread inundation is imminent or expected (typically tsunami forecast amplitudes over 1 m).

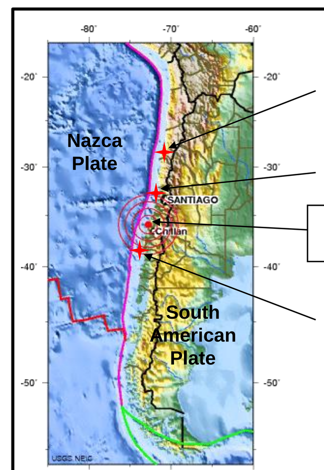


Figure 1: Chilean earthquake epicenter
(altered from http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2010tfan.php#details)

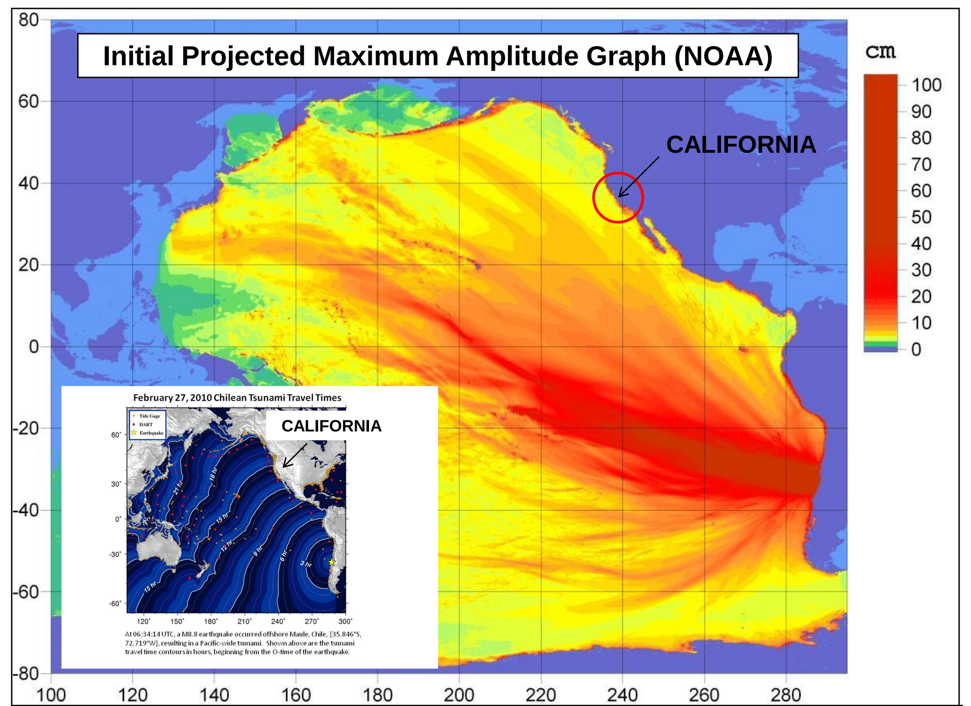
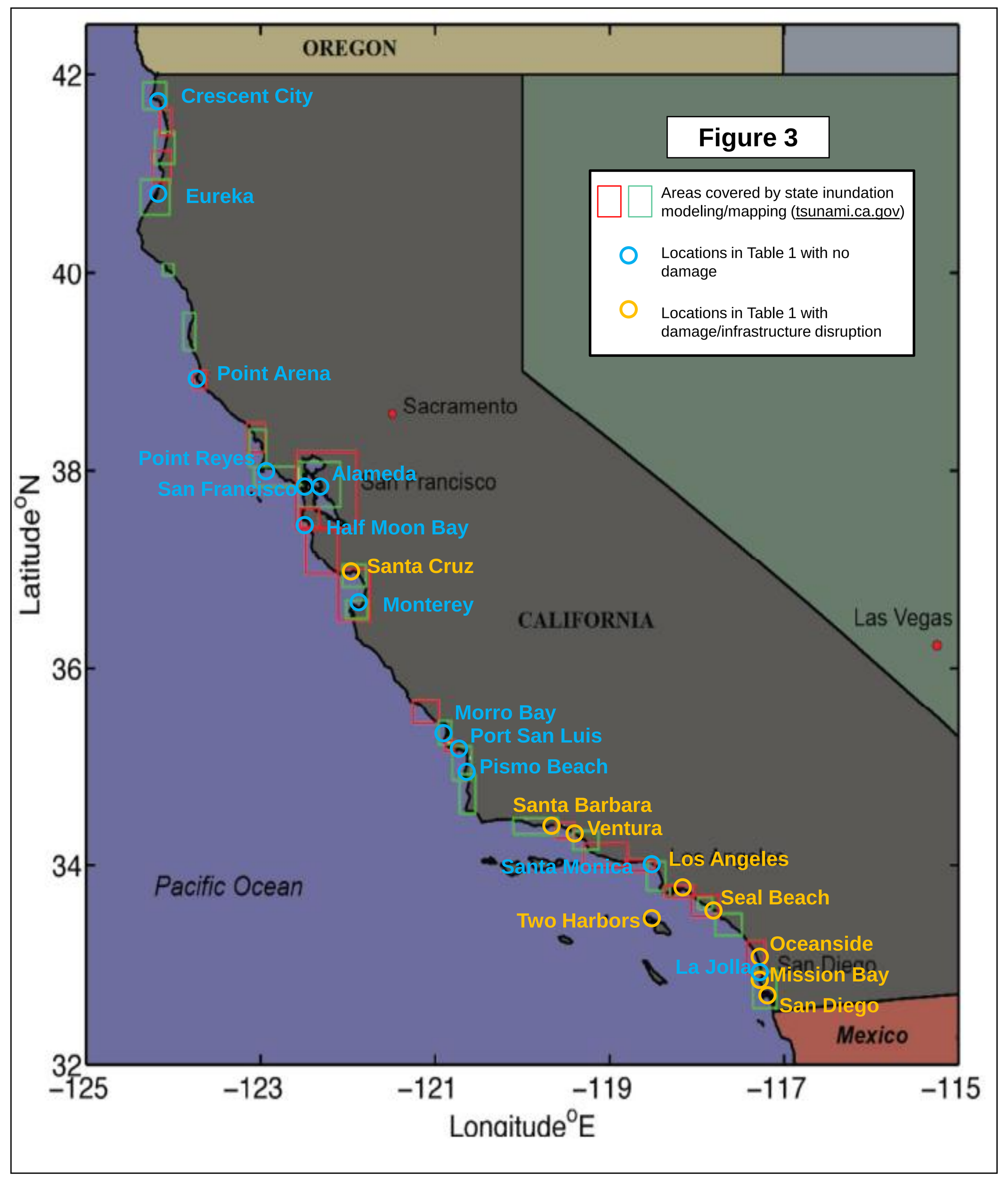


Figure 2
(from http://wcatwc.arh.noaa.gov/previous.events/Chile_02-27-10/Tsunami-02-27-10.htm)



	Maximum Tsunami Amplitudes			First Arrival Times		Estimated	
	Forecasted (meters)	Observed Tide Gauges (meters)	Estimated By Others (meters)	Forecasted (PDT)	Observed Tide Gauges (PDT)	Maximum Current Speeds (knots)	Reported Damage or Other Effects from Tsunami (NDR = no damage reported)
Crescent City	0.61	0.64		1340	1346		NDR
Eureka	0.2	0.23		1336	1333		NDR
Arena Cove	0.49	0.39		1248	1304		NDR
Point Reyes	0.46			1259	1259		NDR
Alameda	0.18	0.12		1344	1345		NDR
San Francisco	0.22	0.32		1320	1326		NDR
Half Moon Bay	0.96		0.6				NDR
Santa Cruz	0.51		0.9			8-10	minor damage to boats and marine infrastructure
Monterey	0.45	0.36		1231	1243		NDR
Morro Bay	0.82		0.5			4-6	NDR
Port San Luis	0.84		0.8				NDR
Pismo Beach	1.43		0.9-1.2				NDR
Santa Barbara	0.75	0.91		1230	1231	8-10	minor damage to dredging equipment
Ventura			0.6-0.9			12-15	over 20 docks damaged; buoys moved
Santa Monica	1.18	0.64		1225	1225		NDR
Two Harbors/Catalina			0.6-0.9				minor damage to several docks
Los Angeles	0.77	0.42		1215	1215	4-6	minor damage to docks and marine infrastructure
Seal Beach							minor flooding from storm and tsunami surges 24 hours later
Dana Point			0.5-0.7			10-12	bait barge severed
Oceanside			0.4			5-8	several buoys carried out to sea; boat trailer swamped
La Jolla	0.84	0.60		1202	1202		NDR
Mission Bay						8-10	small sailboat swamped trying to leave harbor; buoys moved
San Diego	0.27	0.40	0.6	1204	1208	12-15	damage to docks, concrete piers, and boats

Table 1: Data from WCATWC and field surveys/observations; see Figure 3 for locations.

EVENT RESPONSE TIMELINE

February 26-27, 2010 - Tsunami Alert Messages for California from the NOAA/NWS WCATWC

Supplemental information from Federal and State Agencies

22:34 PDT (Feb. 26) – Earthquake occurs in south-central coastal region of Chile

#1 - 22:49 PDT (Feb. 26) – Mw 8.5 Information Statement
Earthquake occurred in Chile that may produce tsunami

22:43 PDT (Feb. 26) - USGS: Preliminary Mw 8.5.

23:11 PDT (Feb. 26) - CGS contact with CalEMA Duty Officer discuss 1) approximate travel time to California (13-14 hours), 2) arrival at low tide increasing strong currents in harbors/bays, and 3) that event could end up as Advisory. Previous earthquakes in south-central Chile range from two Mw 8.2s in 1906 and 1943 that created small amplitude tsunamis in California (0.02m to 0.1m), and the massive Mw 9.5 earthquake of 1960 which caused widespread tsunami damage in California (Figure 1; Lander and others, 1993).

#2 – 23:52 PDT (Feb. 26) - Mw 8.6 Information Statement
Tsunami generated in Chile

~23:20 PDT (Feb. 26) – USGS downgrades earthquake to Mw 8.3 and then upgrades to Mw 8.6.

~00:00 PDT (Feb. 27) – USGS upgrades earthquake Mw 8.8.

#3 – 00:57 PDT (Feb. 27) - Mw 8.8 Information Statement

#5 – 02:55 PDT - Mw 8.8 Advisory
- Provided first tsunami arrival times to the minute for four locations along California coast ranging from 12:02 to 13:46.
- Suggested strong current hazards for extended time.

03:00 to 20:00 PDT – WCATWC provided State with additional information on expected and measured tsunami arrival times and amplitudes.

#9 - 07:04 PDT - Mw 8.8 Advisory
- Provided tsunami amplitudes for eight locations in California, ranging from 0.5m to 1.0m, all Advisory levels.

08:00 to 18:30 PDT – WCMs and CalEMA with support from CGS provided local jurisdictions with updated information from the WCATWC, and guidance on the tsunami effects that they can expect to see and actions that they should consider taking on clearing beaches and limiting access to harbors.

#15 - 13:05 PDT - Mw 8.8 Advisory
- First report of measured amplitude and arrival time.

13:00 to 18:30 PDT – CGS phone calls with CalEMA providing field observations of tsunami in San Luis Obispo County. Reported low tides helping minimize effects/hazards on beaches. Strong currents in Morro Bay still active into the evening.

#16 - 13:47 PDT - Mw 8.8 Advisory
- First report of damage (Ventura Harbor).

#22 - 20:03 PDT – Tsunami Advisory Cancellation

Tsunami Effects in California

Information about the effects of the tsunami was available from eyewitness accounts, questionnaires, on-line articles and videos, and field measurements by several of the co-authors. Table 1 shows WCATWC tsunami forecast amplitude and arrival time estimates, measured data from tide gauges, and observations from various sources (this data is still being collected and therefore should be considered a partial data set). The effects from this event were more severe than the recent 2009 Samoa tsunami for California (Wilson and others, 2009).

- **Large tidal fluctuations (initially at low tide)**
  - Maximum 2m to 2.5m (peak to trough) observed on beaches in Pismo; drawdown dramatic in some places (Figure 4)
  - Peak amplitude on West Coast 0.91m measured in Santa Barbara Harbor (Figure 5); note peak occurs 5 hrs after first arrival
- **Strong currents**
  - Strongest at harbor entrances and within narrow channels
  - Up to 15 knots in several southern California harbors (Figure 6)
- **Significant erosion/scour**
  - Moderate along beaches and river mouths
  - Ventura Harbor reported dredging savings from scour (approximately $100k)
- **Damage**
  - Docks, boats, harbor infrastructure, minor flooding; several million dollars statewide (Figure 6 and 7)
  - Harbors: Santa Cruz, Santa Barbara, Ventura, Los Angeles, Two Harbors/Catalina, Dana Point, Mission Bay, and San Diego with flooding in Seal Beach following day (Figure 8)
- **Extended tsunami activity (over 24 hrs)**
  - Strong surges continued into evening, observed in Mission Bay and Morro Bay (Figure 8)
  - Following morning, storm surge plus tsunami activity produced flooding at Seal Beach (Figure 9)

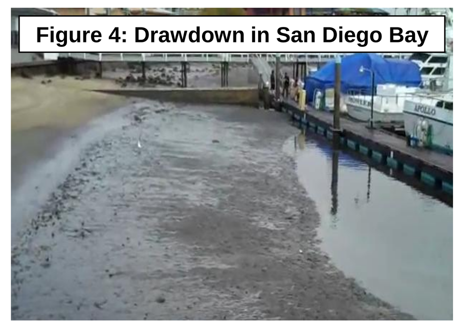
Figure 4: Drawdown in San Diego Bay


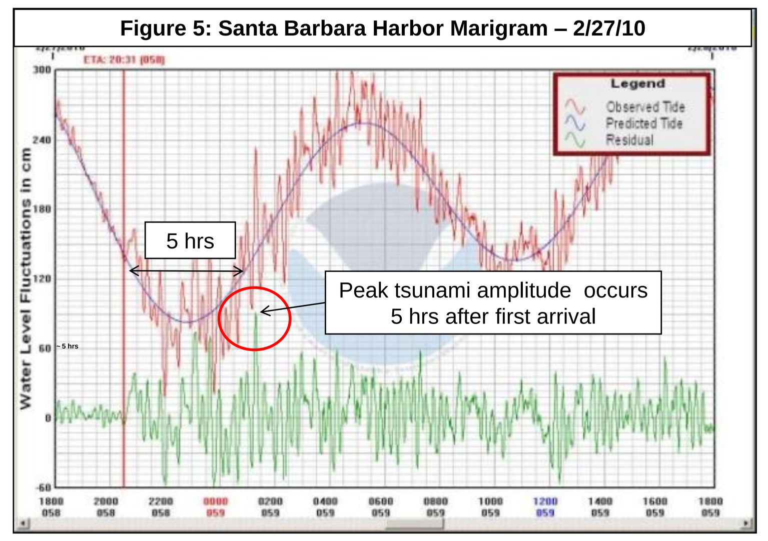
Figure 5: Santa Barbara Harbor Marigram – 2/27/10


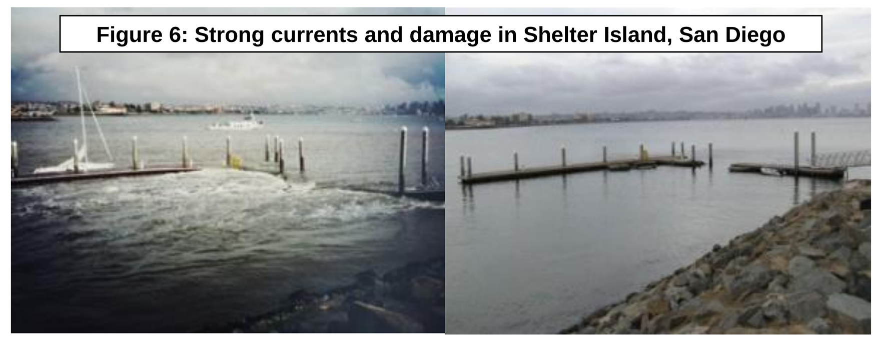
Figure 6: Strong currents and damage in Shelter Island, San Diego


Figure 7: Damage to docks in Ventura Harbor

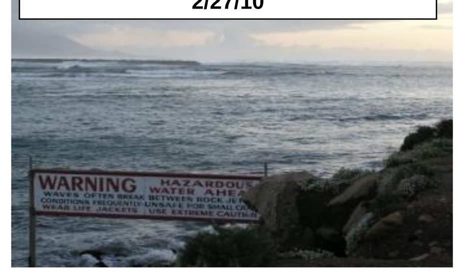

Figure 8: Morro Bay - 18:30 PDT 2/27/10


Figure 9: Seal Beach – following morning (2/28/10)


Lessons Learned - Harbors

- **Avoid outside sources for alert information or actions**
  - Some areas reported hearing alert level changed to "Warning" when it had not
  - Others called off response too early because they thought it safe
- **Don't underestimate power of "small" tsunamis (Figure 10)**
  - Harbors caught off guard by strong currents
  - Beach activity not as noticeable because of low tide
- **For Advisories, keep boats at docks in harbors before arrival**
  - Yes…Small boats docked in areas protected from strong currents
  - No…Large boats can cause drag on and damage docks
- **Don't take boats out of harbor during tsunami**
  - Harbor response boats struggled while patrolling harbors
  - Swamped boat at mouth of Mission Bay
- **Don't try to reenter harbors too soon**
  - Strong currents make navigation difficult many locations
  - Boat owners must understand length of tsunami activity

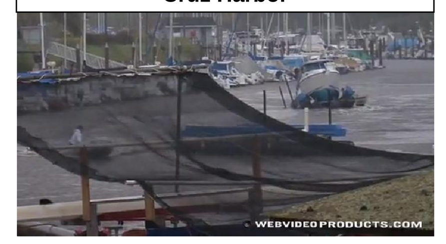
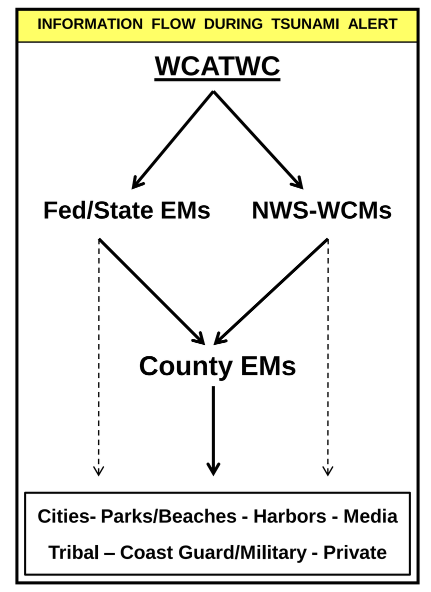
Figure 10: Boats broke loose in Santa Cruz Harbor


Figure 11: Very generalized information flow diagram to help reduce misinformation during event


What Needs Work

- **Clarify what a "Tsunami Advisory" means**
  - Improve guidance, communication, and outreach
  - Update local emergency response plans
  - Consistent alert levels between NWS Warning Centers
  - Consistent response by local jurisdictions
- **Prevent miscommunication about alert status**
  - Clearly document correct line-of-communication (Figure 11)
  - Recommend counties establish formal response to Advisories
  - Continue to educate alert status definitions
  - Highlight and streamline updated information on alert statements
  - Better communication through use of field observers (e.g. CGS)
- **Understanding length of Advisory and response "fatigue"**
  - Improve education about length of event
  - Expand training to backup emergency managers (EMs)
  - Increase scientific/CGS support to state and regional EMs
- **Improve support for maritime community**
  - Encourage inclusion of port and harbor EMs in county workshops, work groups, and State Steering Committee
  - Provide better guidance about actions during events

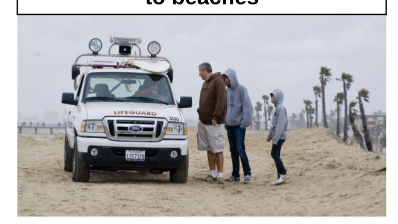
Figure 12: Patrols limited access to beaches


Figure 13: Field measurements being taken (Santa Ana River).


Implementing New Strategies

Geoscientists at the federal, state, and local level implemented several new response strategies during this event:

1. The WC/ATWC **increased the number of forecasted tsunami arrival time and maximum amplitude values** provided to the state from five to 30. With more information to use, local jurisdictions were better able to determine the appropriate response activities.
2. Because of the 13-1/2 hour time window between the tsunamis generation and its daytime arrival in California, more **scientists deployed** themselves to the coast prior to the tsunami's arrival. Some observations helped confirm what the WC/ATWC noted on tide-gauge marigrams during the event: Advisory level tsunami amplitudes were active for up to 8 hours after the first wave arrival.

Validated by the field experiences of geoscientists during the two recent Advisories in California from the Samoa and Chile tsunamis, the NTHMP is funding the state's development of **pre- and post-tsunami field teams and a centralized information clearinghouse** for future Tsunami Advisories and Warnings. The plan includes enlisting the help of 30 to 40 field geoscientists that can be deployed to collect information about the tsunami similar to those deployed during this event. The field teams will be developed during 2010-11 and the plan will be ready for operation if needed by 2011. To help initiate its development, the tsunami clearinghouse organizers will collaborate with the existing earthquake clearinghouse established in California.

Acknowledgements and References

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